Tensile Properties of Maize Stalk Rind

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Experiments were carried out to measure the tensile properties of maize stalk rind. Two varieties of maize stalk (SD 12 and SD 9) and two moisture contents (fresh and air-dried) were tested. From each maize stalk sample, nine specimens (test coupons) of stalk rind were prepared to represent nine internodes from the bottom to the top of the maize stalk. The rind specimens were subjected to uniaxial tensile loading at a slow rate of 3 mm/min. From the recorded load-elongation curves, tensile stresses, modulus of elasticity, and tensile energy were determined. It was found that maize stalk rind exhibited elastic-plastic behavior, *i.e*., stress initially increased with strain in a linear fashion, and then nonlinearly until rupture. The measured ultimate tensile stress ranged from 178.15 to 80.53 MPa (average 122.26 MPa), elastic modulus from 35.01 to 11.38 GPa (average 19.32 GPa), and tensile energy from 0.004 to 0.099 J (average 0.032 J). Tensile strength, elastic modulus, and tensile energy decreased from the bottom to the top of stalk. There was a significant difference in tensile strength, modulus of elasticity, and tensile energy among two varieties and two moisture contents.

Keywords: Maize stalk rind; Tensile strength; Modulus of elasticity; Moisture content

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INTRODUCTION

Maize stover is produced in relatively large quantities throughout the world (Sokhansanj *et al*. 2002; Klingenfeld and Kennedy 2008) and offers enormous potential as a renewable and domestic feedstock for bioenergy and fiber production. However, the characteristics of maize stover, such as being difficult to harvest and having low bulk density, variable composition, poor flow ability, and storage instability, are major barriers against its usage. There is a need to improve harvesting, processing, and bulk handling systems that are capable of separating the more valuable components and densifying the material for transportation and processing. Successfully designing and developing those systems requires knowledge of the mechanical properties of maize stover (Wright *et al.* 2005).

Many studies have been carried out to investigate mechanical properties of maize stalk for various purposes, such as designing harvest equipment, designing biomass processing equipment, crop loading, and studying how to utilize fibers in maize stalk. Igathinathane *et al.* (2011, 2009) tested high- and low-moisture maize stalks using a linear knife grid size reduction device to determine ultimate shear stress and cutting energy. Prasad and Gupta (1975) conducted experiments to determine the optimum values of bevel angle, knife approach angle, shear angle, and knife velocity for cutting maize stalks. Kaliyan and Morey (2009) studied the densification process of maize stover grinds by using a non-linear elasto-visco-plastic model under uniaxial compression conditions. Mani *et al.*

(2006) conducted tests in which chopped maize stover samples were compacted in a piston cylinder under three pressure and moisture content levels to produce briquettes. Maize stalk has been used as a reinforcement in polypropylene composites. Rodriguez *et al.* (2010) determined that the intrinsic tensile strength of maize stalk cellulosic fibers was 460 to 670 MPa. In a study of comparing mechanical properties of maize stalk fiber with common textile fibers, Reddy and Yang (2005) measured the tensile properties of maize stalk fibers, and indicated that the structure and properties of maize stalk fibers were suitable for producing various textile products. Several researchers (Panthapulakkal and Sain 2007; Nourbakhsh and Ashori 2010) studied and compared wheat straw, maize stalk, and corncob as reinforcements for thermoplastics and concluded that mechanical properties possessed by these materials were suitable for using as reinforcements. Stalk strength impacts corn yield and silage quality due to its relationship with stalk lodging and stover quality (Peiffer *et al.* 2013).

Maize stalk is a complex material from the point of view of mechanical strength; the structural composition of the rind is the chief determinant of strength (Peiffer *et al.* 2013). Few studies have been focused on the mechanical properties of maize stalk rind. The objective of this study was to determine the tensile property of maize stalk rind, as affected by its location (height) on the stalk and moisture content.

EXPERIMENTAL

Maize Stalks

The maize stalks used in this study were from maize varieties SD12 and SD9 planted in Yangling, Shaanxi, China, on May 6 and 11, 2013. The field plots consisted of eight rows with 23 plants per row at a space of 60 cm within the row and 30 cm between the rows. Plots were fertilized before planting according to soil test results. Manual weed control was done during the growing season. Field irrigation followed the farmers' normal practices in the region. The plants were manually harvested (cut and cleaned) on August 15, 2013. The plant heights varied from 1.90 to 2.27 m at harvest. Of the two varieties of maize (SD12 and SD9), both used as commercial crop cultures, the stalk of SD12 grows stronger than that of SD9, and the average diameter of SD12 is about 20.07 mm in the lower stalk. However, the stalk of SD9 is taller and the average height is over 2.0 m.

Specimen Preparation

A total of 150 maize stalks were selected for testing. Each maize stalk had nine internodes, numbered as #1 to #9, from the bottom to top. To prepare a test specimen, the apex internode of the plant was first removed and the rest of the stem was cut between nodes (Fig. 1). Then, a 90-mm section was cut as the test section. The literature has shown that the properties of a maize stalk may vary with height (Meng 2005). Therefore, each section at a certain height was treated as an independent sample. Because the rind provides most of the mechanical strength to the stalk (Zhao and Yuan 2003), this study focused on the rind properties between internodes at different heights. A 90-mm section was cut, then the rind was split lengthwise with a knife, and the core was carefully removed from the rind. Because there are no standards for preparing tensile test specimens for maize stalk rind, the principle of testing metal and plastics was followed (ASTM A370 2010). The test specimen had two shoulders and a gauge (test) section in between (Fig. 2). The test section had a smaller cross-section of 1 mm wide by 1 mm long to allow the deformation and failure to occur in this section, whereas the larger 8 mm wide shoulders provided enough area for easy gripping. The prepared specimens were immediately sealed in separate plastic sample bags and stored in the refrigerator (5 °C) (Tavakoli *et al.* 2009a). After that, the specimens were taken out of the refrigerator and allowed to stay at room temperature for about 2 h. Tensile tests were carried out at 23 °C and 48% relative humidity.

Fig. 1. Photograph showing internodes of maize stalk

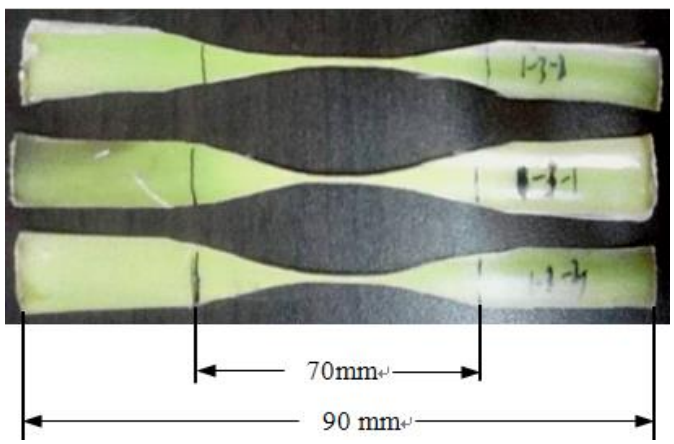


Fig. 2. Maize stalk rind specimens prepared for tensile test

Experimental Equipment and Procedure

A universal testing machine (DDL10, EDC-controller, Germany and China, Fig. 3) was used to perform tensile tests on the prepared rind specimens.

Fig. 3. Schematic diagram of the universal testing machine

The equipment had five components: a holding hydraulic clamp (stationary clamp), a pulling hydraulic clamp (moving clamp), a driving unit, and a data acquisition system connected to a computer. The specimen was installed on the test machine by clamping the two shoulders of the specimen through the two hydraulic clamps. The test machine had a maximum loading capacity of 10 kN. A computer data acquisition system recorded the magnitude of the applied load to the specimen and elongation of the specimen. A loading speed of 3 mm/min was used for all tests in order to avoid velocity influence (Wright *et al.* 2005).

The mechanical properties of maize stalk vary with its moisture content (Ince *et al.* 2005). Two moisture levels were tested in this study and were 70% w.b. (wet basis) of fresh stalks and 10% w.b., which was obtained by air-drying the stacks for three months. The moisture content of maize stalk was determined by the oven method at 103 °C for 24 h (ASABE S269.4 2007). Nine replicates were conducted for each of the three treatments (2 maize varieties × 2 moisture levels × 9 heights), resulting in a total of 360 tests.

The load-displacement curves recorded by the data acquisition system were used to derive the mechanical properties of maize stalk rind. The maximum tension load (load at which stem failure took place and the peak of the load-displacement curve) was used to calculate the maximum tensile strength (stress) as follows (Eq. 1),

$$\sigma_{max} = \frac{P_{max}}{A} \quad (1)$$

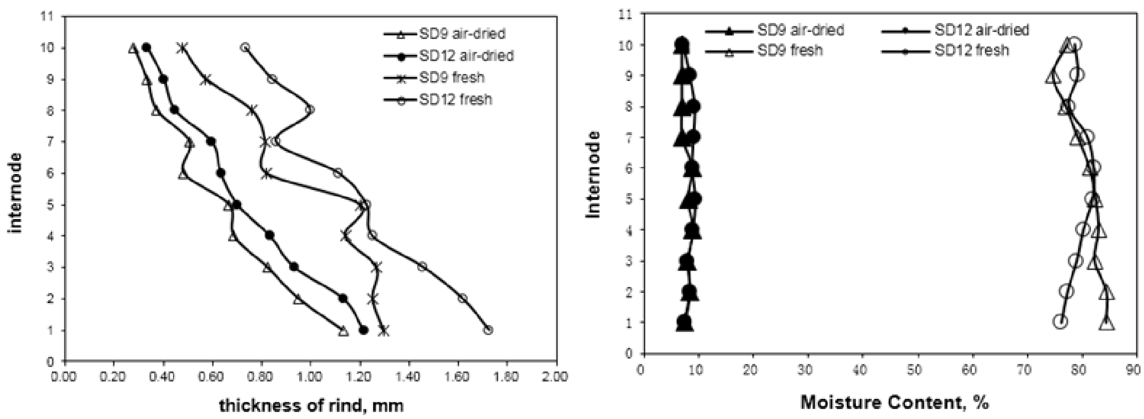
where σ_{max} is the maximum tension stress in MPa, P_{max} is the maximum load in N, and A is the tested cross-sectional area of specimen in m^2. The modulus of elasticity of stalk rind was determined as the slope of the linear section of the measured stress-strain curve.

RESULTS AND DISCUSSION

Characteristics of Maize Stalk Rind

Figure 4(a) contains details of the rind thickness of SD12 and SD9 at two moisture content levels. Rind thickness of maize stalk ranged from 0.28 to 1.73 mm. The effect of internodes height on rind thickness showed an increase from top to bottom. The mean increase rate was 9.65%.

Figure 4(b) shows that the moisture content was invariable across fresh and air-dried states. The moisture contents keep in constant from bottom to top. The value of moisture content at fresh states was 8%, and the air-dried was 80%.



(a) (b)

Fig. 4. Variation trend of the thickness of rind (a) and moisture content (b) for fresh and air-dried specimens

General Loading Behavior

A typical load-elongation curve had four sections (the loading started at the end of the initial flat section; Fig. 5). In the first elasticity section, the elongation grew while load was kept constant. In the second linear elasticity section, load increased linearly with elongation, and the slope of this linear section reflected the modulus of elasticity of the rind. After the linear section, the elongation increased quickly while the load grew slowly until it reached a maximum value. In the last stage, load started to decrease while elongation continued until a rupture occurred.

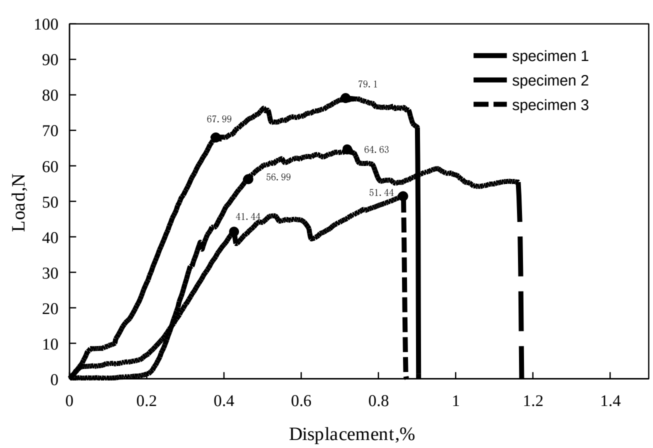


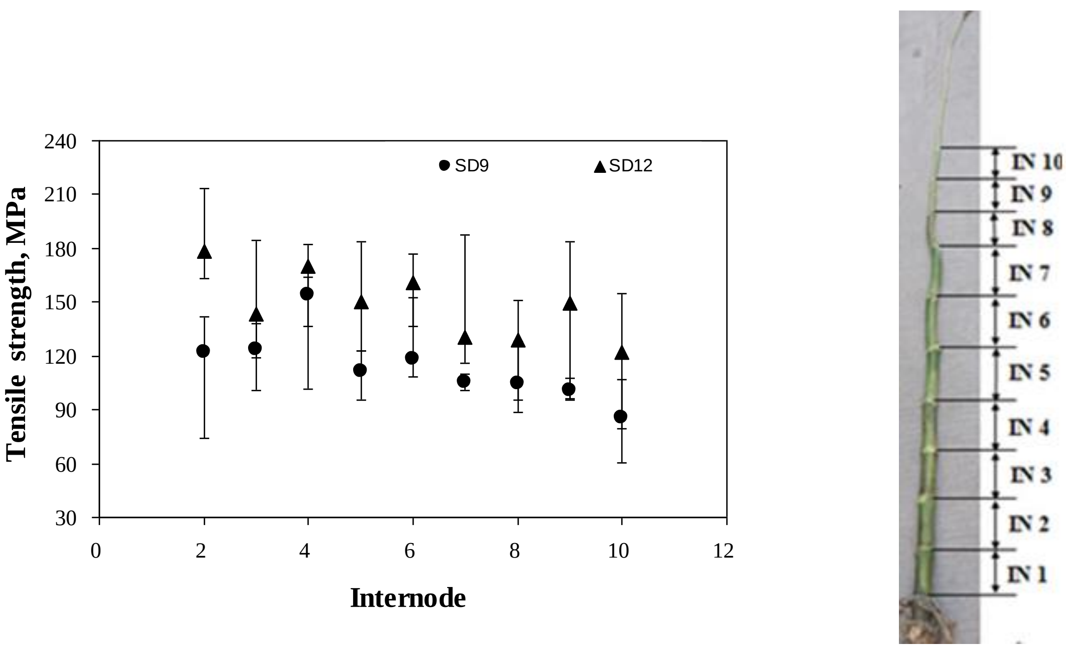
Fig. 5. A typical load -displacement curve of the specimen

The surface of rupture was fibrous (Fig. 6), which indicated that the failure consisted of many slight tension failures (failures of individual fibers), producing a ragged break.

Fig. 6. Ruptured surface

Tensile Strength

Tensile strength varied with stalk height; higher strength was found in the lower section of the stalk (Fig. 7). For example, the maximum tensile strength in the lower section was 178.15 MPa, while it was 122.09 MPa at the top nodes for variety SD12. A similar trend was observed for variety SD9. Analysis at different internode locations indicated that the effect of height on rind strength was significant ($P<0.05$) for both SD9 and SD12. The lower section of maize stalk is stronger and the rind is thicker. Shinners *et al.* (1987) reported that the lower section was the older part of the plant and had higher lignin content. Lignification causes cell walls to thicken, which greatly increases their rigidity. Variation of strength along stem height was also reported by O'Dogherty *et al.* (1995) for wheat straw and by Nazari Galedar *et al.* (2008) for alfalfa stems.

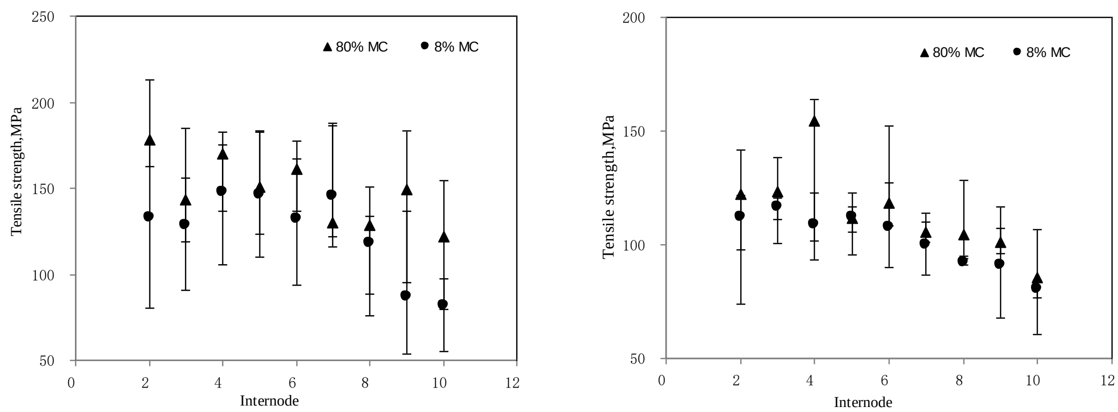


(a) (b)

Fig. 7. Variation of tensile strength of maize stalk rind along the height at 80% moisture content (fresh stalk); (a) strength and (b) locations of internodes

There was a significant difference (P<0.05) in strength between the two varieties (Fig. 7(a)). The strength of SD12 varied from 122.09 to 178.15 MPa with a mean of 148.17 MPa at 80% moisture content, and from 81.68 to 147.55 MPa with a mean of 124.35 MPa at 8% moisture content. In comparison, the mean value of tensile strength for SD9 was 114.04 MPa, (ranging from 85.65 to 154.31 MPa) at 80% moisture content, and 102.48 MPa (ranging from 80.53 to 116.94 MPa) at 8% moisture content. These values were similar to those reported by Hou and Jiang (2013).

The strength for fresh stalk (80% MC) was higher than that for the dried stalk (8% MC) (Fig. 8). Paired t-tests indicated that the moisture content effect on strength was statistically significant for variety SD12, but not for SD9. For SD12, the moisture effect had a considerable difference at the lower and upper portions.



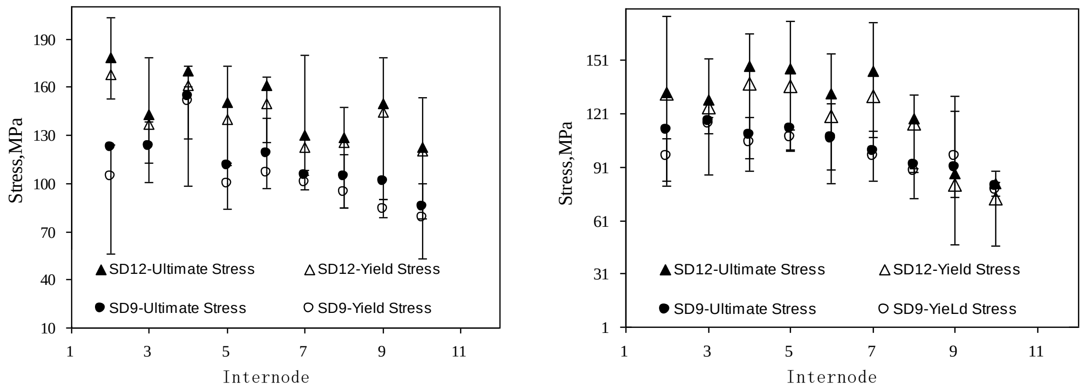
(a) (b)

Fig. 8. Tensile strength of maize stalk rind at 80% (fresh) and 8% (air dried) moisture contents. (a) Variety SD12 and (b) Variety SD9.

Tavakoli *et al.* (2009b) demonstrated that the shear strength of barley straw increased with increasing moisture content (10 to 20% w.b.). In contrast, Galedar *et al.* (2008) found that the tensile strength of alfalfa increased with decreasing moisture content. O'Dogherty *et al.* (1995) demonstrated that the tensile strength of wheat straw was not consistent with varying moisture content. These discrepancies have been discussed in the literature, and it is believed that the main reason for the differences is that the stalk tissues have heterogeneous structure for varieties of the same stalk, allowing for the 'shifty' strength to be revealed under different conditions.

Yield Stress

The yield stress curve was found to be similar to the ultimate stress (Fig. 9). The yield stress value was 7% to 17.3% lower than the ultimate stress.

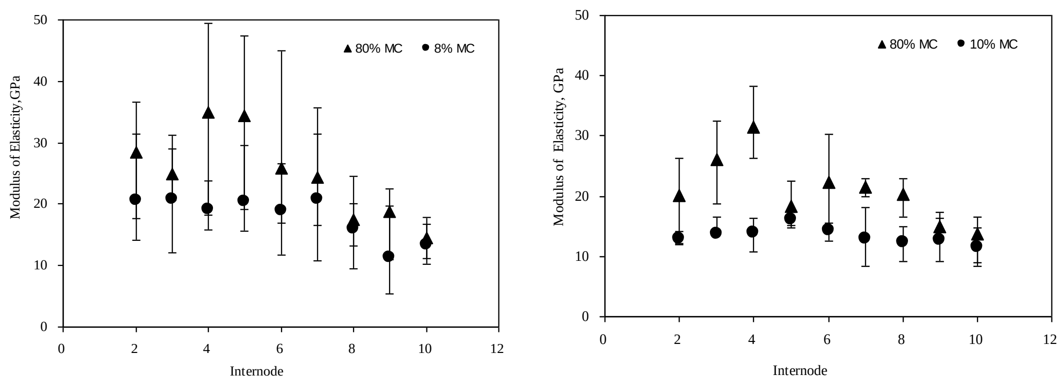


(a) (b)

Fig. 9. Tensile strength of maize stalk rind of two varieties (SD12 and SD9) and moisture contents. (a) MC=80% (fresh) and (b) MC=8% (air dried)

Modulus of Elasticity

Modulus of elasticity was generally higher in the lower section than that in the upper section of the stalk (Fig. 10). This was again attributed to the higher lignin content in the lower section of the plant. The modulus of elasticity at the lower moisture level was lower than that at higher moisture level ($P<0.05$; Fig. 10).



(a) (b)

Fig. 10. Modulus of elasticity of maize stalk rind at 80% (fresh) and 8% (air dried) moisture contents. (a) Variety SD12 and (b) Variety SD9

Limited information on the stiffness (modulus of elasticity) of plant stems can be found in the literature (Chattopadhyay and Pandey 1999), although the reported observations of moisture effect on the modulus of elasticity have been inconsistent. Schulze (1953) reported that the bending stiffness of grass stems decreased drastically (by 50%) when moisture content decreased from 86% to 74% w.b., but stiffness changed little when moisture decreased from 74% to 60% w.b. Decreasing moisture content from 60% to 30% w.b. resulted in a 50% decrease in stiffness in some cases, but nearly no decrease in others. Sun *et al.* (2013) reported that the flexural modulus of elasticity of maize stalks increased from 147 to 339 MPa when the moisture content decreased from 90% to 10%.

CONCLUSIONS

1. Tensile strength (136.26 MPa for SD12 and 108.26 MPa for SD9) and modulus of elasticity (19.32 GPa) were experimentally determined for two varieties of maize stalk rind in their natural state. The average value of maize stalk rind thickness was 0.87 mm (1.07 mm for fresh and 0.69 mm for air-dried).
2. The typical load-elongation curves were obtained and were shown to be similar to mechanical properties of elastic-plastic material. The tensile strength and elastic modulus of the top section of the maize stalk was less than the lower section. The tensile strength of different varieties showed great disparity. The modulus of elasticity with high moisture is higher than with the low moisture.
3. The results from the study are relevant to the development of handling equipment, such as maize harvester and cutting machine. The results may also contribute to the further use of maize stalk fibres in industry.

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